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Direct diode lasers for industrial laser cutting: a performance comparison with conventional fiber and CO_2 technologies

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Abstract

The direct use of diode lasers for cutting sheet metal has high potential to decrease operational costs, but, currently, implementation in industrial environments is constrained by beam quality. In this paper the performance of a novel *direct diode* laser (DDL) with increased beam quality is documented for both fusion and flame cutting and compared to conventional CO_2 and fiber laser sources. Experimental tests were carried out for steel and aluminium based on a Design of Experiments approach. Furthermore, an analytical model, focusing on the absorption of lasers in metals, is described here, which predicts and clarifies performance variation. Although the observed laser beam quality is still lower than the other studied technologies, industrially relevant cutting speeds, with acceptable surface quality, are achievable with DDL, as validated by our results

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Keywords: Laser cutting; diode laser; absorption; beam quality; optimization

1. Motivation and state of the art

Even though laser cutting of metal sheets is a well-established process, a demanding market in terms of process quality and overall costs makes any further improvement a possible product differentiation. Decreasing investments and operational costs are thus common targets. The type of laser source is the main influencing factor in this context. Diode lasers have the potential to decrease operational costs considerably: high-power broad-area diode lasers are the most efficient laser sources[1]; the characteristic high ratio output power per unit weight allows for optimal use of space [2]; the wavelength versatility gives the possibility for a targeted selection with respect to metal absorption or "eye-safety" radiation [3]; maintenance is low and expected lifetime high for the common diode lasers systems [4]; fully automated production of the optical components and further assembly is possible, decreasing investment costs [5].

So far, the implementation of diode lasers as direct sources for laser cutting of metal sheets has not been possible due to the low laser beam quality achievable in these systems. This can be illustrated by means of the Beam Parameter Product (BPP): Fig. 1 shows a plot of data gathered in the International Laser Symposium of 2014 in Dresden, mapping typical laser processing regions to different beam qualities and powers of the available laser systems in the current market. Recent developments in beam coupling techniques, used to scale up the power of diode lasers, significantly improve the beam quality, enabling the application in demanding processes like laser cutting. Advances in common coupling techniques has been achieved by several manufacturers: side-by-side beam coupling is used for conventional diode-laser arrays and requires well-designed micro-optics,

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while polarization and wavelength coupling have improved due to better optical coatings [6, 7]. Furthermore new techniques are promising to achieve beam qualities comparable with multimode fiber and disk lasers: stacking single emitters in a step mode [8]; wavelength combination of bars using granting mirrors [9]; and use of beam quality converters [10].

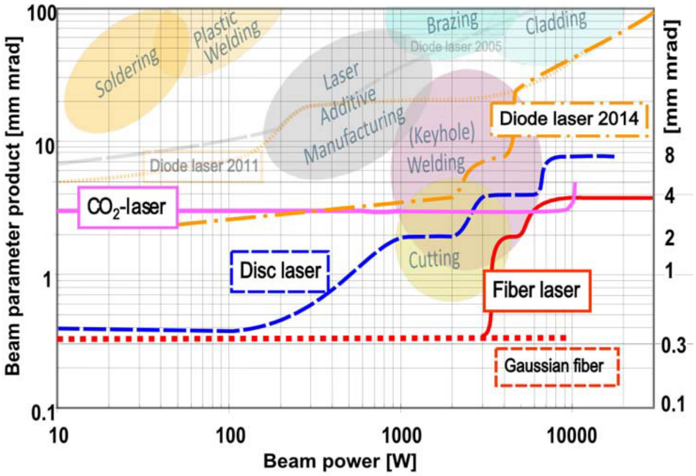


Fig. 1. Comparison of laser systems (based on data presented during the 2014 International Laser Symposium, Dresden).

While it is clear that, as a result of recent developments, diode lasers achieve a beam quality adequate to be used for laser cutting of sheet metal, the exact boundaries determining the necessary beam quality and power are not yet clear. A common premise states that the best beam quality will lead to the best cut performance. The lack of experimental data in literature regarding laser cutting with diode lasers grants no validation for this assumption. In this work a novel DDL with a BPP of 24.6 *mm mrad* was evaluated for laser fusion cutting and flame cutting of several materials following a methodology based on *Design of Experiments* (DOE). A comparison was made with established technologies in this application domain: CO_2 (BPP of 12.6 *mm mrad*) and fiber (BPP of 3.4 *mm mrad*) lasers. Furthermore, an analytical model based on the Fresnel absorption in metal surfaces is used in order to understand the impact of different wavelengths, beam geometries and powers on the cutting performance. Finally it is concluded that industrial relevant cutting speeds, with acceptable cutting quality, are achievable with the current technology.

2. Experimental setup and design of experiments

For the experimental work, a diode laser source with 2 kW nominal power, guided through an optical fiber of 400 µm, was used in a CNC gantry machine. Details concerning power measurements in different stages of laser delivery, beam analysis and electrical power consumption are presented in [11]. The source is composed by four modules with different powers and wavelengths. Each module is obtained using optical stacking and polarization coupling techniques. All four diode beams are superposed by wavelength coupling and finally guided through an optical fiber. A Precitec cuting head with a 150 mm collimating lens and three optional focusing lenses, 80, 125 and 150 mm, was used. Fig. 2 shows the output of a beam analysis for a 125 mm focusing option using a FM35 FocusMonitor device from PRIMES. The BPP was found to be 24.6 *mm mrad*.

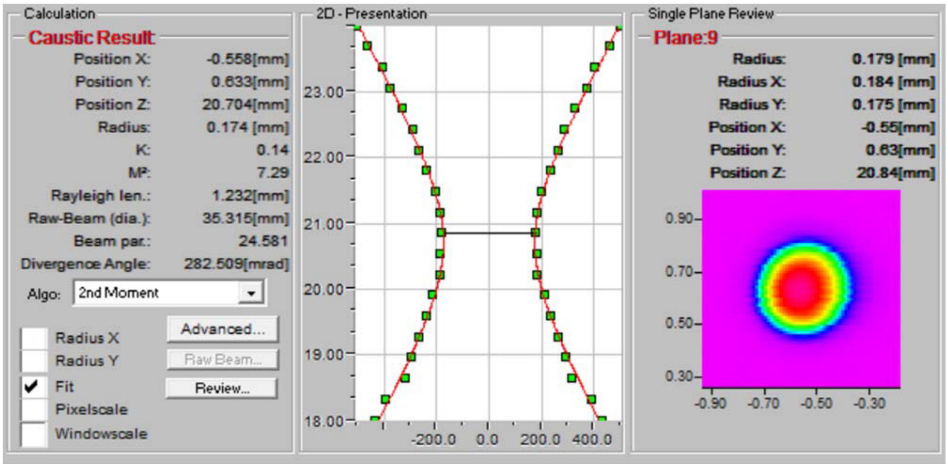


Fig. 2. Caustic measurement of the diode laser beam with a 125 mm focusing lens.

The materials used in the cutting experiments were selected in order to represent the most common industrially relevant materials, while obtaining data for a broad spectrum of possible processes and absorption behaviours. Aluminium (AW-5083 for 1 mm, AW-5086 for 2 mm and AW-5754 for 4 and 6mm) and stainless steel 304 L were cut with nitrogen to study fusion cutting with different absorption characteristics. To represent the process of flame cutting, structural steel (S235 for thicknesses up to 4 mm and S355 for thicker sheets), was used.

A systematic procedure based on DOE was used for the cutting tests in order to obtain well-optimized cutting parameters, in terms of cutting speed, for each combination of material and thickness. An example for 1 mm thick stainless steel is given in [11] while a more detailed description can be found in [12]. For the optimized set of parameters, the cut quality was evaluated according to UNI EN ISO 9013. Roughness was measured with a Taylor-Hobson Form Talysurf-120L roughness measurement machine, while the cut edge inclination angle was determined with a Mitutoyo FN905 3D CMM Quickvision Microscope. The final classification was given according to the worst result of these two types of measurements and normally falls into the stringent (0), intermediate (I) or moderate (II) categories. If no match is found the sample cannot be classified (N).

3. Absorption behavior for different sources

Inherent source characteristics, such as beam quality, power and wavelength, ultimately define the achievable surface quality and cutting speeds for different materials and thicknesses. Until today, CO_2 lasers are the standard in cutting thin as well as thick metal sheets. These sources are here characterized as 10 µm radiation. High brightness fiber and disk lasers, with a ten times shorter wavelength, are most used for thin sheets where the performance is better than for CO_2. High power diode laser sources have in general a worse laser beam quality than fiber and disk lasers, but similar wavelengths, close to 1 µm. Considerably different absorption behaviour is to be expected for the described wavelengths. The influences of wavelength, beam quality and power on the absorption in both iron and aluminium are described next.

Beam absorption in metallic surfaces is highly dependent on the angle of incidence and on the optical properties of the metal. This relation is defined by the Fresnel reflection equations on opaque materials for parallel (s-) and perpendicular (p-) polarization states [13]:

$$R_p = \frac{(n.\cos\emptyset_{in} - 1)^2 + (k.\cos\emptyset_{in})^2}{(n.\cos\emptyset_{in} + 1)^2 + (k.\cos\emptyset_{in})^2}$$

$$R_s = \frac{(n - \cos\emptyset_{in})^2 + k^2}{(n + \cos\emptyset_{in})^2 + k^2}$$

The refractive index, n, and the extinction coefficient, k, are optical parameters of the material dependent on plasma, laser and collision frequencies. Using the properties in Table 1 and the theory presented in [14], these parameters were calculated for iron and aluminium as proxies for the studied steel and aluminium alloys. The s- and p- absorption refers to different relations between the plane of polarization (defined by the electric vector and the propagation direction) and plane of incidence (includes the propagation direction and the surface normal). For p- absorption the planes are coincident while for s- absorption they are perpendicular. The absorption for circular or random polarization states is commonly modelled as an average of these two polarization states [15].

$$A_{Ave} = 1 - R_{Ave} = 1 - \frac{R_p + R_s}{2}$$

Table 1. Material properties for pure iron and aluminium [16].

Property	Unit	Iron	Aluminium
Number of weakly bound valence electrons	-	2	3
Atomic weight	-	55.8	27.0
Melting temperature	[K]	1808	933
Boiling temperature	[K]	3008	2333
Average temperature of molten material, T_{Ave}	[K]	2408	1633
Mass density at T_{Ave}	$[\mathrm{kg\ m^{-3}}]$	6502	2135
Electrical resistivity at T_{Ave}	$[\Omega\ \mathrm{m}]$	145×10^{-8}	34×10^{-8}

Fig. 3 shows the plot of absorptivity for both iron and aluminium as a function of the incident angle for 1 and 10 µm radiations. The Brewster angle is defined when the absorption reaches a maximum. This happens for one specific incident angle in the studied cases for both materials, the maximum absorptivity of 1 µm radiation occurs for smaller incident angles compared to 10µm radiation. Furthermore, around the Brewster angle the absorption is less sensitive to variations in the incident angle then for 1 µm radiation. However, very close to 90°, the 10µm radiation is strongly absorbed by the studied materials.

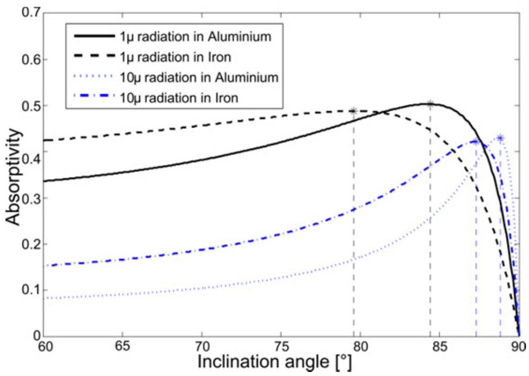


Fig. 3. Absorption in function of the laser incidence angle for different wavelengths on iron and aluminium.

In laser cutting the cut front is usually inclined to angles close to 90° relative to the sheet metal surface. The strong dependence of the absorption on the angle of incidence of the laser beam indicates that the energy absorbed during laser cutting will be dependent on the cutting kerf geometry and thus also on the beam intensity distribution and cutting parameters. Recent research has proven experimentally that the cut front inclination angle decreases with increasing cutting speed until it is no longer covered by the beam, and the cut is typically lost [17]. Other authors, after measuring the cut front, propose that the most efficient condition occurs when beam and cut front are coupled in a way that less energy is lost due to beam transmission without interaction with the material [18]. If we assume a relation between beam geometry, cut front inclination and material thickness as shown in Fig. 4, absorption can be plotted as a function of the sheet thickness for a specific optical and laser setup. Fig. 5 shows the results for the laser setups considered in this work for the absorptivity in aluminium and iron. A high absorption, close to the Brewster angle value, is expected in both materials for the diode laser configuration for the whole range of thicknesses.

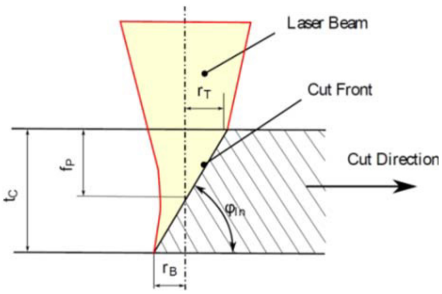


Fig. 4. Cut front inclination angle at maximum cutting speed (after [14]).

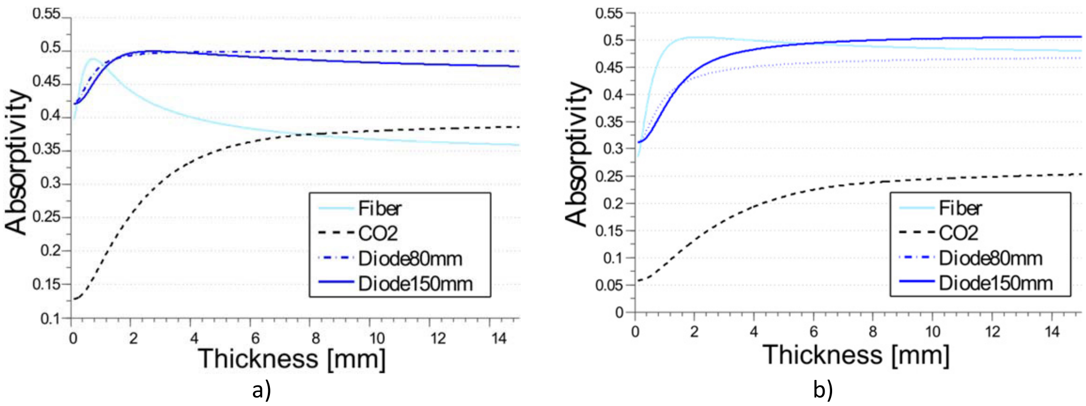


Fig. 5. Absorption in (a) iron and (b) aluminium in function of the sheet thickness for the studied optical and laser configurations.

4. Results and analysis

The optimized cutting results for each combination of material and thickness are presented in Table 2. A clear difference in terms of surface quality and thickness limits is found for the two studied cutting regimes. Flame cutting of structural steel yields an acceptable surface quality, in agreement with the UNI EN ISO 9013 standard, for thicknesses up to 10 mm. In case of fusion cutting of both stainless steel and aluminium the surface quality is considerably worse for thicknesses higher than 2 mm where the cut samples did not reach the quality classes of ISO 9013. It is worth mention that this is a very strict norm and that the surface quality needed depends often on the application. The lower surface quality is mainly due to the poor roughness of the cut edge which is characteristic for 1 µm radiation. In fact several authors studied this problem for fiber and disk lasers and suggested some reasons for this phenomenon: Scintilla et al. predicted a low cut front temperature for the 1 µm radiation which is responsible for a higher viscosity of the molten material and a more difficult expulsion by the assist gas [19, 20]; Hirano et al. found a relation between the angular dependence of the absorption in metals and instabilities in the melt that lead to higher roughness for 1 µm cut samples [21]; Petring et al. studied the effect of multiple reflections on the surface quality and found that for 1 µm radiation, besides the positive effect in terms of higher cutting speed, the higher reflections were also responsible for a destabilization of the lower cutting zone leading to coarser striations[22].

For a better performance overview of the studied DDL source in sheet metal cutting, the optimized cutting speeds are compared with the speeds applied on established CO_2 and fiber laser machine platforms (Fig. 6). For fusion cutting the DDL setup achieved a higher cutting speed than a CO_2 source with the same output power. This difference is even more pronounced for aluminium sheets, as expected from the absorption calculations in Section 3. For thin sheets the fiber laser has clearly the best performance in fusion cutting, which is mainly due to the higher energy density as a result of a better beam quality. The best cutting results regarding the diode laser setup were obtained for flame cutting, where the diode laser achieves similar cutting speeds as CO_2 and fiber lasers with equivalent output power. In flame cutting around 40% of the process energy is added to the process by the exothermic oxidation reaction [23], but the oxygen and the laser power balance each other to achieve a stable cut [24]. This partially explains the more homogenous cutting speeds for the different sources at the same output power. A higher power allows higher cutting speeds for thick sheets, as can be seen in figure 6c, where the performance of the 4kW CO_2 laser setup is better than the other systems considered. On the other hand, the high energy density of the fiber laser and the higher power of the CO_2 4kW are not giving an advantage for thin sheets, as seen for fusion cutting. Powell et al. studied the exothermic reaction of oxygen with steel sheets in detail and proved that a too high energy density can stop the oxidation reaction and thus lead to reduction in cut quality and maximum achievable cutting speed [25].

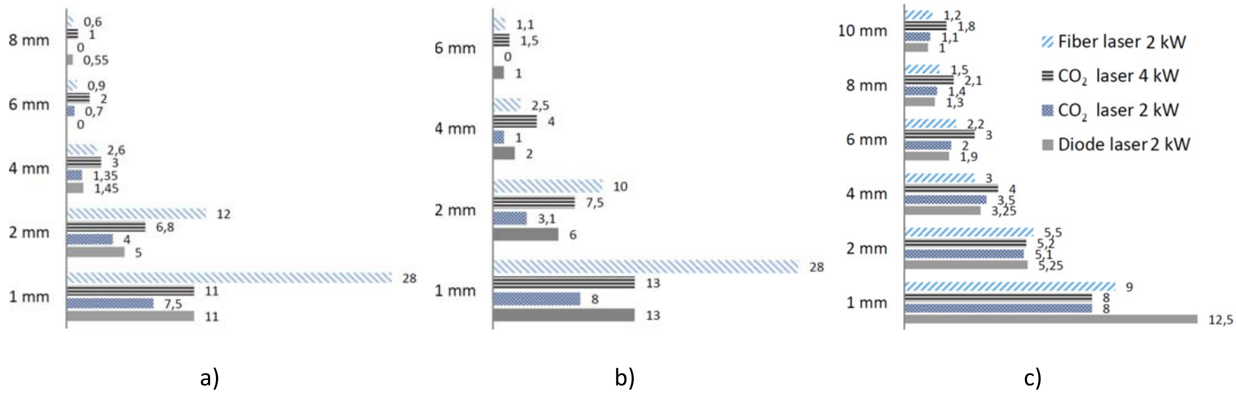
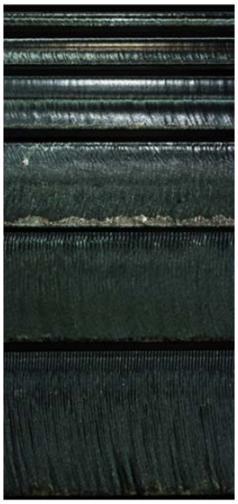
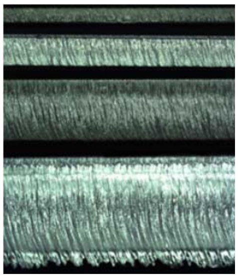
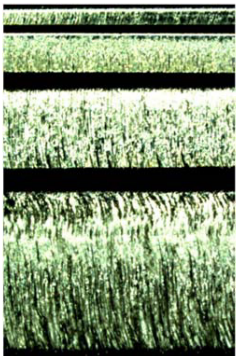


Fig. 6. Achievable cutting speeds [m/min] for different sources in: fusion cutting of (a) stainless steel and (b) aluminium, and (c) flame cutting of structural steel.

5. Conclusions and future work

The DDL source analysed in the present study was found to be capable of cutting the tested materials at industrially relevant cutting speeds, with an acceptable cutting quality, revealing the potential for the implementation of diode lasers in laser cutting as a direct source. For the flame cutting process, samples with good surface quality and speeds similar to cuts performed on a fiber and a CO_2 laser were achieved. For the fusion cutting process and at the same output power, the cutting speed was higher that of a CO_2 source but lower than the reference fiber laser, while the surface quality was good only for thin sheets. Furthermore the theoretical considerations regarding absorption in metals helped to understand the differences in cut performance for these laser sources. Future work will focus on increasing the coupling of the beam through changes in beam geometry, both through the use of adequate optics and by using diode laser sources with better beam quality.

Table 2. Cutting results with the diode laser setup.

Thickness [mm]	Material	Pictures	EN ISO 9013 quality class	Cutting speed [m/min]
1	S235		0	12,50
2	S235		I	5,25
4	S235		I	3,20
6	S355		I	1,90
8	S355		I	1,30
10	S355		II	1,00
1	EN AW-5083		I	13,00
2	EN AW-5086		I	6,00
4	EN AW-5754		N	2,00
6	EN AW-5754		N	1,00
1	304 L		I	11,00
2	304 L		I	5,00
4	304 L		N	1,45
8	304 L		N	0,55

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